Optical Pulse Synthesis using Brillouin Selective Sideband Amplification

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We present a novel concept for Fourier synthesis of optical pulses using Brillouin selective sideband amplification in optical fibers and demonstrate the generation of a 7.8 GHz optical pulse train using two CW lasers and two phase modulators.

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Optical pulse generation using Fourier synthesis is attractive for a number of applications, including photonic A/D conversion, electro-optic sampling, and time-resolved spectroscopy, because the bandwidth, shape, and repetition rate of the pulses can be easily controlled. Previously reported optical pulse synthesis involved locking several CW lasers together,either with a linear phase-locking scheme [1] or with some other nonlinear phase-locking schemes [2,3]. In this paper, we report a simple scheme that uses Brillouin selective sideband amplification (BSSA))[4,5] to generate necessary frequency bands which are automatically phase-locked together. Other advantages of this scheme include built-in optical amplification, simple electronic control, polarization insensitivity, and direct conversion of low phase noise RF signal into low jitter optical pulses.

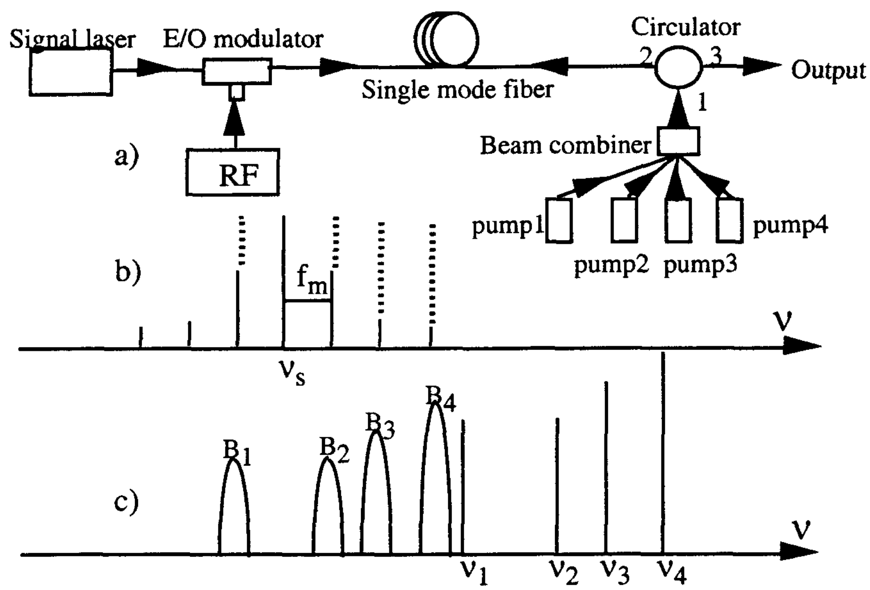

Fig. 1 Illustration of the concept of BSSA assisted Fourier pulse synthesis. B_i is the gain peak generated by ν_i.

The concept of BSSA assisted pulse synthesis is illustrated in Fig. 1a. Light from a CW signal laser is first modulated by a RF signal of frequency f_m after passing through an electro-optic modulator. The modulated light beam with a spectrum shown in Fig. 1b then enters a long length of optical fiber. Optical beams from several CW pump lasers enter the long length of fiber from the opposite end, as shown in Fig. 1a. Each pump beam induces, via the eletrorestrictive effect, an acoustic grating moving in the direction of the pump beam along the fiber. Part of the pump beam is then scattered backwards by this moving grating and produces a frequency down-shifted (due to the Doppler effect) light beam (Stokes wave) propagating in the direction of the signal laser [6], as shown in Fig. 1c. The frequency down shift is about 12.8 GHz for a 1319 nm pump beam and 10 GHz for a 1550 nm pump beam if a standard single mode fiber (Corning SMF-28) is used. By tuning the frequency of either the pump laser, the signal laser, or both, the frequency of the backscattered light can be made to coincide with one of the phase modulation sidebands of the signal laser. The interaction of this sideband, the grating, and the pump will further enhance the induced acoustic grating, causing more backscattering of the pump and greatly amplifying the sideband. The gain of the amplification can be adjusted by controlling the pump power. Several modulation sidebands can be amplified by several pump beams to prescribed levels, as shown in Fig. 1c. The interference of the sidebands in the time domain then produces a train of optical pulses with desired width, repetition rate, and spectrum.

In the demonstration shown in Fig. 2, we use a single pump laser and a phase modulator to replace the multiple pump lasers in Fig. 1 and thus lower the cost. In addition, because previously reported Brillouin amplification is known to be polarization sensitive[7], we implemented a polarization insensitive scheme to overcome the polarization sensitivity. Another advantage of this double-pass scheme is that it enhances the small signal Brillouin amplification gain by a factor of two for a given fiber length.

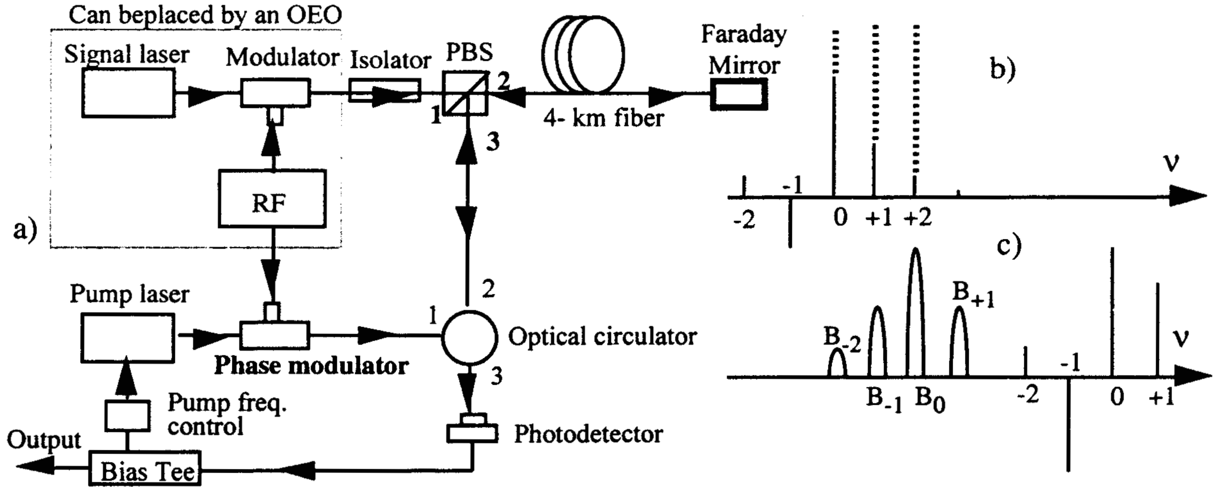

Fig. 2 Experimental setup for demonstrating BSSA assisted Fourier pulse synthesis. The vertical lines show the relative phases and amplitudes of the modulation sidebands.

As illustrated in Fig. 2a, light from the signal laser (diode pumped YAG) first passes through a phase modulator and is modulated by a RF signal at 7.7 GHz. The modulated signal beam, whose spectrum is shown in Fig. 2b, then enters a 4-km single mode fiber spool via a polarization beam splitter (PBS). The polarization state of the signal beam is adjusted to be aligned with the passing axis of the PBS. At the other end of the fiber spool, the signal beam is reflected by a 90° Faraday mirror so that the polarization state of the reflected light is always orthogonal to the forward going light everywhere along the fiber. Consequently, the reflected signal beam is directed toward the circulator by the PBS and finally enters the photodetector.

On the other hand, the pump beam from another diode-pumped YAG laser at 1319 nm is also modulated by the same RF signal and is directed to enter port 3 of PBS via the circulator. The polarization of the pump is so adjusted that the pump beam exits port 2 of PBS and enters the single mode fiber spool. At other end of the fiber spool, the pump beam is reflected back by the Faraday mirror so that the polarization state of the backward-going pump beam is orthogonal to the forward-going pump beam everywhere along the fiber. Finally, the pump beam exits port 1 of PBS and is attenuated by the isolator. It is important to note that the forward-going pump beam always has the same polarization state of the backward-going signal beam, which allows optimized Brillouin amplification everywhere along the fiber and eliminates polarization sensitivity of the Brillouin amplification process[7].

The sidebands of the phase-modulated pump beam and the corresponding Stokes frequencies are shown in Fig. 2c. The carrier frequency of the pump laser is so adjusted that its Brillouin gain peak (labeled B_0) is coincided with the +2 modulation sideband of the signal beam, as shown in Fig. 2b. Because both the signal and pump beams are modulated by the same signal, other Brillouin gain peaks generated by the corresponding modulation sidebands of the pump beam are automatically aligned with the corresponding modulation sidebands of the signal beam. The modulation depth of the pump and signal beams are carefully adjusted so that the three amplified signal sidebands have about the same amplitude, as shown in Fig. 2b and 2c. We chose to amplify the in-phase upper sidebands to obtain clean optical pulses. We also implemented a simple circuit to prevent the relative frequency drift between the signal and the pump lasers. The circuit is based on the fact that when the signal sidebands are optimally amplified, the received DC signal in the photodetector is also significantly increased.

Using a bias tee to monitor the DC signal from the photodetector, the frequency of the pump laser can be easily controlled by maximizing the DC signal.

Figs. 3a-3c show the optical spectra of the synthesized pulse train measured with a super-cavity spectrum analyzer under different conditions: a) the pump is turn off, b) the un-modulated pump is tuned to amplify the +2 modulation sideband of the signal beam, and c) the pump is modulated and is tuned to the same frequency as in b). In the experiment, the total pump power entering the 4-km fiber is about 30 mW and the total receive optical powers at the photodetector are 2.5 mW for Fig. 3a and 8.3 mW for Fig. 3c.

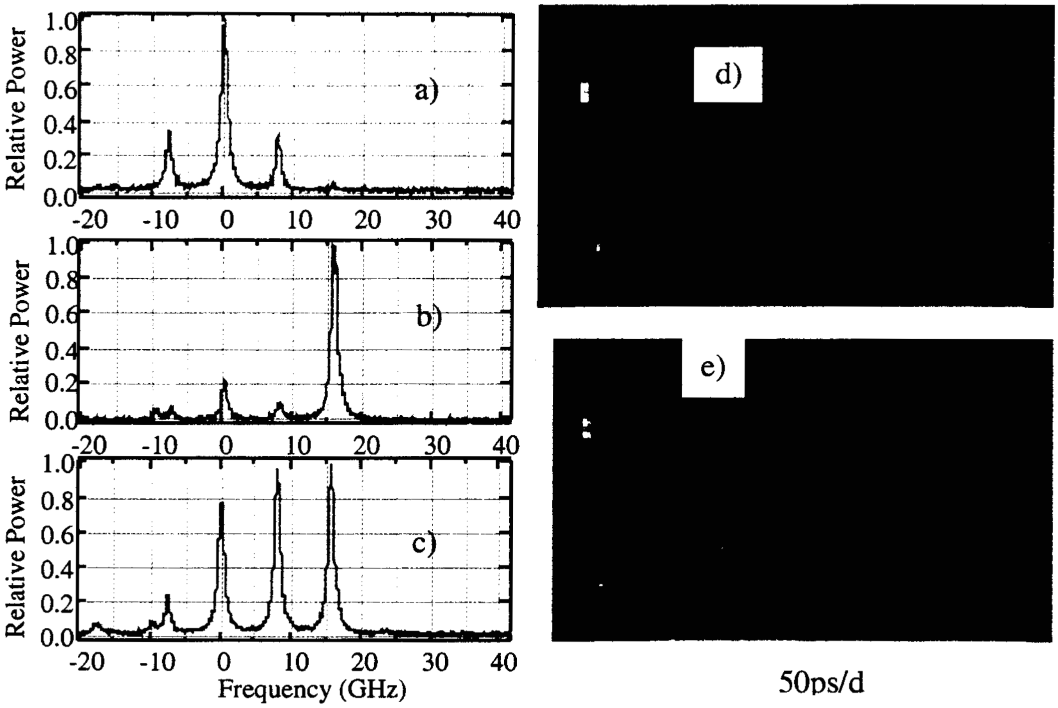

Fig. 3 Experimental results

We also measured the synthesized pulses in time domain with a 20 GHz photodetector and a fast sampling scope (Tektronix CSA803A with a SD-26 sampling head), and the results are shown in Figs. 3d and 3e. Fig. 3d corresponds to the spectrum of Fig. 3b while Fig. 3e corresponds to the spectrum of Fig. 3c. No temporal response was observed for the spectrum of Fig. 3a because of the nature of the phase modulation. It is evident from the experimental results that a train of optical pulses with a repetition rate of 7.7 GHz is successfully synthesized using the described novel scheme. By tuning the frequency of the pump laser to amplify different signal sidebands and adjusting the modulation depth of the pump beam, different pulse shapes were also observed.

In summary, we described the concept of BSSA assisted optical pulse synthesis and successfully demonstrated the generation of a train of optical pulses with two CW lasers and two phase modulators. As indicated in Fig. 2, the method can be used to directly convert the low jitter signal generated by the Opto-electronic oscillator (OEO) [8] to optical pulses for photonic A/D conversion applications.

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